A METHODOLOGY FOR THE QUANTITATIVE TREATMENT OF VARIABILITY AND UNCERTAINTY IN PERFORMANCE-BASED ENGINEERING ANALYSIS AND/OR DECISION ANALYSIS WITH A CASE STUDY IN RESIDENTIAL FIRE SPRINKLERS

by

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A Methodology for the Quantitative Treatment of Variability and Uncertainty in Performance-Based Engineering Analysis and/or Decision Analysis with a Case Study in Residential Fire Sprinklers

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SUMMARY

Implementation of any form of a performance-based standard will require many decisions to be made. These decisions will be more difficult, more complex, and more uncertain than under a prescriptive-based code. This paper presents a methodology which quantitatively treats variability and uncertainty and applies it to a complex fire protection engineering problem. The methodology is both rigorous and user-friendly. It does not require quantification of all uncertainties in an analysis. A three-phase approach is utilized which identifies those variables with ranges great enough to reverse the final decision and encodes uncertainty on them. Information about the uncertainty of these critical variables is then employed in the analysis. Results are displayed graphically as either discrete or continuous joint probability distributions. The methodology also demonstrates ways of handling value judgments, such as the value of premature death avoided, by means of comparative analysis, parametric analyses, or switchover analysis. This methodology was applied to a model for determining the benefits and costs of residential fire sprinklers. Results from this study provide insights about the merits of residential fire sprinkler systems whish were not evident in previous studies.

1.0 MAKING GOOD FIRE PROTECTION DECISIONS

There have been several publications that conceptualize the implementation of a performance-based building and fire code system in the United States.[1,2] What is clear, although not explicitly stated, is that implementation of any form of a performance-based standard will require more decisions to be made. These decisions will be more difficult, more

[1] Concepts of a Performance-Based System for the United States, Report of the 1996 Activities of the SFPE task Group on Concepts of a Performance-Based System for the United States, Society of Fire Protection Engineers, 1997.
[2] Snell, Jack E., Status of Performance Fire Codes in the USA, VTT-Nordic Fire Safety Engineering Symposium, Finland, 1993.

complex, and more uncertain than under a prescriptive based code. Robert Clemen discusses in his book, *Making Hard Decisions*, four reasons why making decisions is so difficult.[3]

- *First, decisions can be hard simply because of their complexity.* In the case of decisions regarding fire protection features, one must consider the potential for property protection, life safety, injury mitigation, and business continuity. One must also consider the diverse impacts on people with special needs such as the very young, old, or persons with limited mobility.
- *Second, decisions can be hard because the decision-maker may be working toward multiple or competing objectives.* In fire protection analyses, typically competing objectives are low cost and a high level of safety. Progress in one direction such as installing automatic fire sprinklers for increased fire safety may impede progress towards a competing objective such as designing an economical building.
- *Third, a problem may be difficult if different perspectives lead to different conclusions.* In a fire protection decision, the perspective of the building owner, designer, and authority having jurisdiction may very well differ.
- *Finally, decisions can also be hard because of the inherent uncertainty.* Uncertainties may arise in the model physics, the values of the inputs, the reliability of the devices, and the frequency of events. Yet, a decision must be made without knowing for sure what these uncertain values will be. In fact, the most important decisions are often those that must be made under the greatest uncertainty, have the highest complexity, and involve multiple perspectives and goods.

The focus of this paper is on the quantitative treatment of variability and uncertainty. The tools and techniques presented here can help in identifying important sources of uncertainty and representing that uncertainty in a quantitative way. Section 2 discusses the types of uncertain quantities likely to be encountered in a fire analysis, a three-phase approach to conducting such an analysis, and other analysis tools commonly used in the treatment of uncertainty. Section 3 shows how these tools were used in a model of the decision to mandate residential fire sprinklers from a societal cost-benefit standpoint.

2.0 TOOLS AND METHODOLOGY

The first step in the treatment of uncertainty is the identification of the uncertain variables. Uncertainty can take many forms. We can be uncertain of the physical parameters such as the ignition source, the flame spread rate, the heat release rate of furnishings, or the effectiveness of a fire suppression system. We can also be uncertain about human behavioral response to a fire. We can be uncertain of the age or health of people who may be exposed to a fire. There is not one universal technique however that is appropriate for the treatment of all types of uncertainty. Thus, in order to determine the best way to treat the uncertainty, the type of quantity about which the uncertainty exists must be identified. Next, it must be determined if it is crucial to treat the uncertainty quantitatively. Finally, the appropriate methodology or tool must be selected for the job.

[3] Clemen, Robert, Making Hard Decisions: An Introduction to Decision Analysis, Duxbury Press, Belmont, CA, 1990.

2.1 Types of Quantities

There are many types of quantities used in the calculation of a performance-based engineering analysis. These can be classified into three categories: 1) those used as model inputs; 2) those that determine the model structure (i.e., the scope and level of detail of the model); and 3) the selection variables which are used to rank order or choose among possible outcomes. Table 1 shows several types of quantities within each of these categories. Uncertainty exists in many of these quantities and one often finds that this uncertainty is represented in probabilistic terms. Morgan and Henrion argue that *"the only type of quantity whose uncertainty may be appropriately represented in probabilistic terms are empirical quantities".*[4] It is therefore important to distinguish empirical quantities from other types of quantities. Table 2 provides examples of each type of quantity and associated methods appropriate for the treatment of uncertainty.

Model Inputs	Model Structure	Selection Variables
-defined constants	-index variables	-outcome criterion
-empirical quantities	-model domain parameters	-decision variables -value parameters

Table 1. Types of Quantities

Model Inputs
To be empirical, variables must be measurable and have a true value. An excellent reference for uncertainty about an empirical quantity is the "U.S. Guide to the Expression of Uncertainty in Measurement".[5] Empirical quantities in the domain of fire protection engineering include the heat release rate, the burning rate, and the radiative fraction of a given fuel. Defined constants, such as the gravitational constant, are certain by definition. They are discussed here simply to distinguish them from empirical quantities.

Model Structure
Model domain parameters specify the scope of the system being modeled. Model domain parameters are also used to define the level of detail of the model and/or the base line properties. *Model domain parameters are quantities that are often ignored during uncertainty analysis , despite having very considerable potential impact.*[6]

The impact of uncertainty in selecting the model domain parameters cannot be understated. In most fire models, quite different answer result depending on the control volume selected for modeling and the level of detail of the model. This has been shown for fires in high bay spaces. Differences in the outcome criteria such as maximum temperature, and time to activation of fire detectors and sprinklers are found when the large space is modeled with a simple zone fire model vs. a more detailed computational fluid dynamics model.[7] Differences

[4] Morgan, M. Granger and Henrion, M., A Guide to Dealing with Uncertainty In Quantitative Risk and Policy Analysis. Chapter 4: The Nature and Sources of Uncertainty, Cambridge University Press, 1990.
[5] American National Standard for Expressing Uncertainty - U.S. Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540-2-1997, National Conference of Standards Laboratories, Boulder, CO, 1997.
[6] Ibid, Morgan and Henrion, Chapter 4
[7] Notarianni, Kathy A., Comparison of Computer Fire Models to Fire Experiments in a High-Bay Aircraft Hangar, NISTIR 5304, December, 1993.

in the outcome criteria are also found when a large space, which is typically sub-divided by draft curtains,[8] is modeled. If a control volume is drawn around a single draft curtained area, (as opposed to drawing the control volume around multiple draft curtained areas or around the entire building) higher temperatures and faster activation times of installed fire protection devices will be predicted. Also significant to the uncertainty in the outcome parameters are the index variables of the model. Index Variables are used to identify a location in the domain of a model or to make calculations specific to a population, geographic region, etc. Index variables are certain quantities.

Selection Variables

Outcome criteria are defined as the variables used to rank or measure the desirability of possible outcomes. If any of the input quantities upon which an output quantity is dependent is probabilistic, then that outcome criterion is also probabilistic. In fire protection engineering, common outcome criteria are measures of cost and level of life safety provided.

Type of Quantity	*Examples*	*Treatment of Uncertainty*
Model Inputs		
Empirical parameter	Heat release rate, flame spread rate, radiative fraction	Probabilistic, parametric, or switchover
Defined constant	Gravitational constant, universal gas constant	Certain by definition
Model Structure		
Index variable	Time step, geographical	Certain by definition
Model domain parameter	Fire model selected, number of rooms modeled	Parametric or switchover
Selection Variables		
Outcome criterion	Maximum temperature, activation times of devices, net present value	Determined by treatment of its inputs
Decision variable	Level of acceptable fire safety, installation of fire protection devices	Parametric or switchover
Value parameter	Value of life, risk tolerance	Parametric or switchover

Table 2 . Summary of Methodologies for Treatment of Uncertainty Based on Type of Quantity: Adapted from Morgan and Henrion[9]

If a quantity is a decision variable, then by definition it has no "absolute true" value. It is up to the decision maker who exercises direct control to decide its value. Morgan and Henrion state that, "*The question of whether a specific quantity is a decision variable, an empirical quantity, or some other type of quantity depends on the context and intent of the model, and particularly who the decision maker is.*"[10] For example, in performance-based design, the

[8] A draft curtain is a barrier that extends a certain vertical distance down from the roof. Draft curtains are installed to sub-divide a large area with the intent of corralling the smoke.

[9] Ibid , Morgan and Henrion, Chapter 4

[10] Ibid, Morgan and Henrion, Chapter 4

minimum permissible escape time during a fire may be a decision variable for the regulatory body, but it may be an empirical quantity from the viewpoint of the fire protection engineer.

Value parameters represent preferences of individuals. One controversial value parameter is the "value of premature death avoided," often referred to as the "value of life." Another is risk tolerance or risk preference, a parameter used to specify a degree of risk aversion when comparing uncertain outcomes. Although we have seen value parameters treated as empirical quantities and uncertainties about value parameters treated as probabilistic, it is our view that this is rarely helpful and can lead to confusion and/or mask important insights. The effect on the outcome of an analysis caused by differences in value parameters should be demonstrated explicitly. This is done by repeating the analysis for a range of possible inputs of the value parameter(s) to determine if a change in the outcome occurs that someone would care about.

2.2 Stages of an Analysis: A Three-Phase Approach

In this section we propose a methodology for performing a complex engineering analysis which is made up of three phases: 1) deterministic, 2) probabilistic and 3) informational.[11] The approach incorporates techniques for quantifying and propagating uncertainty throughout the engineering analysis and for dealing with variability. It is assumed that the user has identified the nature and types of uncertainty. This approach is illustrated in Figure 1. and described below.

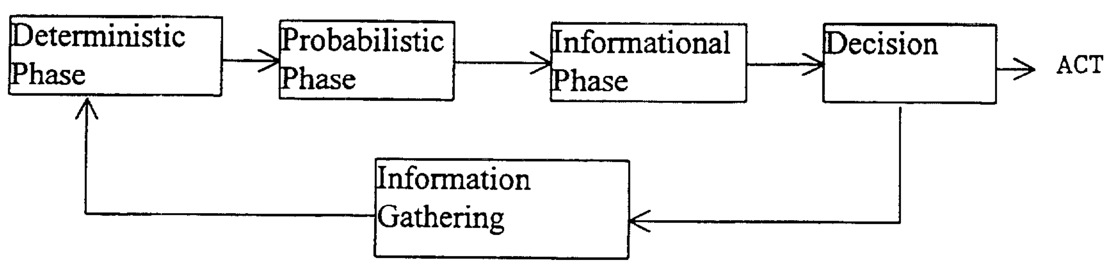

Figure 1. The Decision Analysis Cycle taken from Carl-Axel S. Stael von Holstein[12]

In the deterministic phase, the structure of the decision problem is initially captured in a model where uncertainties in variables are ignored. The inputs are classified into state and decision variables. State variables are defined as those beyond the control of the decision maker. The purpose of the analysis is to find the best setting for the decision variables while considering the best available information on the state variables. To identify the crucial variables (i.e., those with range great enough to change the final decision), a systematic sensitivity analysis is used. Based on the results of the sensitivity analysis, variables are either: 1) set at base (most likely) values, 2) eliminated/combined, or 3) earmarked for treatment of uncertainty in the next or probabilistic phase.

[11] Howard, R.A., Decision Analysis: Applied Decision Theory., In D.B. Hertz and J. Melese (Eds.) Proceedings of the Fourth International Conference on Operations Research., New York: Wiley, 1966.
[12] Stael Von Holstein, C. S, "A Tutorial in Decision Analysis", in Readings on The Principles and Applications of Decision Analysis, edited by Howard, R.A. and Matheson, J.E., Strategic Decisions Group, Stanford University, 1983.

The main purpose of the second phase, the probabilistic phase, is to bring uncertainty into the analysis explicitly. In the probabilistic phase, uncertainty is encoded on the crucial state variables. Also in this phase, risk preferences are dealt with by selection of the outcome criterion that makes explicit the effect of value judgments. The final step in this phase is to determine the best action based on the initial level of information (values and preferences of the decision maker) and then to conduct a probabilistic sensitivity analysis.

In the third or informational phase, the value of additional information is assessed. This can be the value of knowing a particular input better, performing another simulation, conducting more research, or advocating policy changes. The informational phase is concerned with two types of questions. Should more information be gathered before acting on the main decision? What is the worth (in monetary or other measures) of reducing uncertainty in each of the important variables in the problem?

The process outlined above is iterative. After the informational phase, either a decision is made to act or more information is gathered. If additional information is gathered, that information is feed back into the process.

2.3 Analysis Tools

Importance Analysis - An importance analysis determines which of the uncertain input variables contributes most to the uncertainty in the outcome variable. You can then concentrate on getting more precise estimates, or building a more detailed model, for the one or two most "important" inputs. Importance here is defined as the rank order correlation between the output value and each uncertain input. Each variable's importance is calculated on a relative scale from 0 to 1. An importance value of 0 indicates that the uncertain input variable has no effect on the uncertainty in the output. A value of 1 implies total correlation, where all of the uncertainty in the output is due to the uncertainty of a single input.

Sensitivity Analysis - Sensitivity analysis is useful in assessing the consequences of uncertainty in data and in assumptions. By testing the responsiveness of benefit-cost results to variations in values assigned to different parameters, sensitivity analysis allows the identification of those parameters that are most important to the outcome criteria. It does not tell the decision maker the value that should be used, but it shows the impact of using different values.

Parametric Analysis - In parametric analysis, detailed information is obtained about the effect of a particular input on the value of the outcome criterion. This is done by evaluating and plotting the outcome criterion for a sequence of different values for each input, holding the others constant.

Switchover Analysis - A parametric analysis where one or more inputs is varied to find the values (if any) of the inputs that would cause a change in the value of the outcome criteria strong enough to change the final decision.

Comparative Analysis - A technique to evaluate risk and costs to mitigate risk by means of comparison to other similar risks.

Bounding - Evaluating the extremes of the range of possible values of an uncertain quantity.

Expert Elicitation - Where hard data do not exist and are not possible to create, often an expert elicitation is conducted in order to obtain expert judgment of an uncertain quantity. An excellent discussion of the techniques for conducting an expert elicitation are provided in Morgan and Henrion.[13]

3.0 A CASE STUDY IN RESIDENTIAL FIRE SPRINKLERS

A model was built to determine the societal benefits and costs of mandating residential sprinklers. A full description of the mathematical model and the results is beyond the scope of this paper but can be found in, "A Municipal Model of the Cost of Mandating Residential Sprinklers."[14] This paper presents an overview of that study focusing on the techniques used in the treatment of variability and uncertainty and the implications for fire protection analyses.

3.1 Overview of Residential Fire Sprinkler Model

The main influence diagram of the model is shown in Figure 2 below. The model was built using the decision analysis software, Analytica.[15] Analytica allows for input of uncertain variables as probability distributions as well as ease of use of parametric analysis and other analysis tools described above. There are four separate modules that calculate costs and benefits from installation of a residential fire sprinkler system. These modules are shown in bold face type in Figure 2: 1) the mean total installation costs; 2) the reduction in expected value of direct and indirect losses; 3) the reduction in expected value of occupant and fire fighter injuries; and 4) the number of premature deaths averted. This first version of the model did not include benefits that might be realized from reductions in public fire fighting costs. The two outcome criteria are the net cost in dollars per premature death averted and dollars per life-year saved from a residential sprinkler mandate. The net cost is calculated as the difference between the total annual installation and maintaince costs (expressed as annual present value of the life-cycle costs) and the total annual expected benefits. These four variables are shown as hexagonal nodes in Figure 2.

For these calculations, it is assumed that a smoke detector is either present or is installed at the time of sprinkler installation. Benefits attributed to residential sprinklers are those that can be expected above and beyond the benefits of an installed residential smoke detector. Sprinkler systems evaluated here are NFPA 13D or NFPA 13R code compliant.[16] Most cost data is taken from FEMA demonstration projects.[17]

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[13] Morgan, M.G., and Henrion, M., A Guide to Dealing with Uncertainty In Quantitative Risk and Policy Analysis, Chapter 6,Human Judgment About and With Uncertainty, Cambridge University Press, 1990.
[14] Notarianni, Kathy A., "A Municipal Model of the Cost of Mandating Residential Sprinklers," working paper, Carnegie Mellon University, Pittsburgh, PA.
[15] Analytica Manual User Guide, Release 1.0, Lumina Decision Systems, Los Altos, CA, 1996.
[16] NFPA 13D, One and Two Family Dwellings and Manufactured Homes Standard for the Installation of Sprinkler Systems, National Fire Protection Association, Quincy, MA, 1996.
[17] FEMA, Residential Fire Sprinkler Retrofit Demonstration Project, Phase I: Multifamily Structures, U.S. Fire Administration, Emmitsburg, MD, June, 1989.

Region of Country	Community Size	House Type	House Age
Northeast	250,000 or more	One and Two Family Dwelling	New
North Central	100,000 to 250,00	Multi-Family	Retrofit
South	50,000 100,000	Mobile Home	
West	25,000 to 50,000		
	10,000 to 25,000		
	5,000 to 10,000		
	2,500 to 5,000		
	2,500 or less		

Table 3. Index Variables

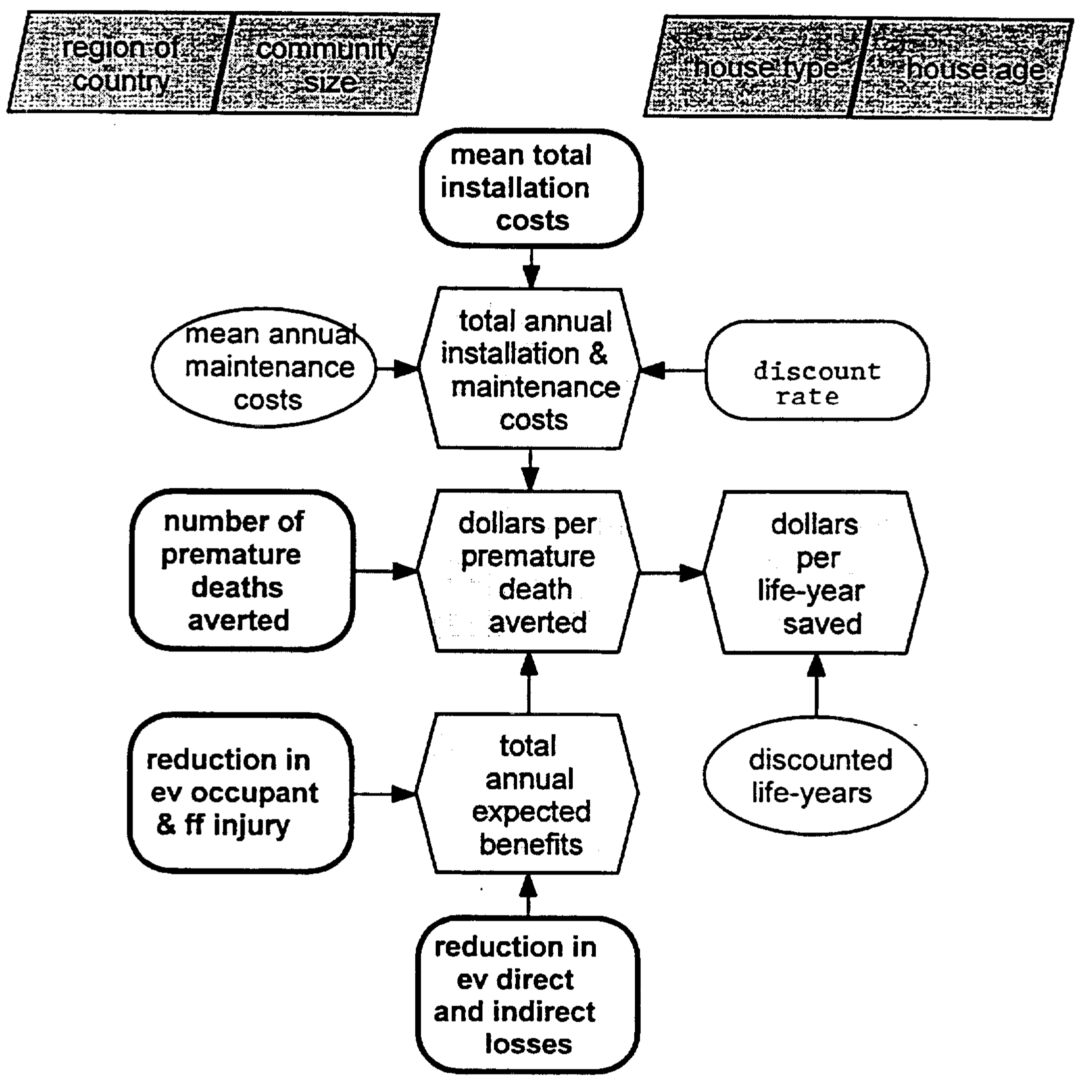

Figure 1. Main Influence Diagram - Residential Fire Sprinkler Model

For comparison to previous studies, calculations of benefits and costs are first presented using national average numbers. The model is then expanded to calculate the net cost per premature death averted for all possible combinations of the index variables. Index variables are shown in Table 3 below. Index variables include the region of the country, the community size, the house type and the house age. Four regions of the country, eight community sizes, three house types, and two house age categories were established. All major input variables to the model are not single value parameters but matrices of values. An example is provided in section 3.2. In all, there are 192 combinations of index variables, thus the model performs 192 separate calculations of the net costs.

3.2 Treatment of Variability and Uncertainty in the Fire Loss Statistics, Costs, and other Empirical Quantities

Inter-Year Variability in the Fire Loss Statistics

To conduct a cost-benefit study of residential fire sprinkler systems, many fire statistics (e.g., death rates, injury rates, and average direct dollar losses) are needed as inputs. National average values of these numbers are often used in these analyses. For example, the national average value for the residential death rate would be equal to the number of residential fire deaths nationally divided by the number of occupied residential units. The actual fire death rate will vary with a number of parameters. The U.S. National Fire Protection Association publishes death rates discretized by three of our four index variables: region of the country, community size, and house type.[18] There are four regions of the country, eight community sizes, and three house types. Thus, the death rate used in these calculations is a 4 x 8 x 3 matrix consisting of 96 values for death rate. Two examples would be the death rate in mobile homes in a community size of 2,500 or less in the South and the death rate in a one- or two-family dwelling in a community size of 25,000 to 50,000 in the West.

Yearly Variability in the Fire Loss Statistics

It is important to differentiate between variability and uncertainty. Variability in the fire statistics from year to year arises because of the randomness of occurrence of fire events. For instance, in one particular year, several large loss fires may occur followed by few or none the next year. In this study, since we are interested in benefits and costs over the life of a fire sprinkler system, mean yearly values were chosen. Yearly variance in the fire loss experience for deaths, injuries, property loss, and indirect losses is thus accounted for by taking mean yearly values over a five year period. Mean values were calculated from the 1989-1993 data.

Uncertainty in the Fire Statistics

Uncertainty in the fire loss statistics exists due to the impossibility of a full and accurate accounting of all fires and all fire losses. Mathematical techniques are thus used to provide estimates.[19] Uncertainty in the fire data is represented as uncertainty about the mean values. An expert elicitation of the chief statistician of NFPA[20] was conducted to set the uncertainty bands for the fire statistics.

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[18] Karter, Michael Jr., U.S. Fire Experience by Region, 1989-1993, National Fire Protection Association, Quincy, MA, 1995.

[19] Hall, John, Jr., and Harwood, Beatrice, The National Estimates Approach to U.S. Fire Statistics, Fire Technology, May, 1989.

[20] Hall, John, Jr., Personal Communication, Uncertainty Bands, 1996.

Uncertainty in other (Empirical) Model Inputs
Uncertainty in the cost data and parameters such as the sprinkler reduction factor were determined by bounding. For example, uncertainty in the sprinkler reduction factor arises because of the small number of fires occurring in homes with automatic sprinklers installed. Data from other occupancies were used to bound the uncertainty.

Propagation of Uncertainty – Once the uncertainties in the model inputs have been expressed, the question becomes, "How can we propagate these uncertainties through the model to discover the uncertainty in the predicted consequences?" In this analysis a Monte Carlo simulation was used. A value for each input is randomly selected from its actual probability distribution. From these values, a value for the outcome criteria is calculated. This process is repeated many times, resulting in a probability distribution for each outcome variable.

3.3 Value of a Life

For any cost-benefit analysis regarding health and safety, one of the most highly contentious points is setting a "value of life." Economists have come up with various ways of estimating the value of a life. These include willingness to pay for safety devices, and income-based estimates.[21] All of these methods remain highly debated. For this study, the problem of establishing a value of life was avoided by means of careful selection of the *outcome criteria*. By selecting the outcome criteria to be dollars per premature death averted and dollars per life-year saved, no explicit value of life needs to be inputted.

3.4 Results

National Average Calculation
Based on a national average calculation, our model predicts that residential fire sprinklers have a median net cost of $7.3M dollars per premature death averted. The probability bands at a discount rate of 8%[22] range from a 0.05 value of $4.2 million (there is a 5% chance that the net cost is $4.2 million dollars or less) to a 0.95 value of $10.7 million dollars (there is a 95% chance that the net cost is $10.7 million dollars or less).

Probability	$M
0.05	4.2
0.25	5.6
0.5	7.3
0.75	9.3
0.95	10.7

Table 4. Dollars per Premature Death Averted National Average Calculation, 8% Discount Rate

[21] Viscusi, W.K., Chapter 4: A Survey of Values of Risk to Life and Health, "Fatal Tradeoffs: Public and Private Responses to Risk, pp. 51-54, Oxford, 1992.
[22] An discount rate of 8% is used as the baseline in this analysis. Discount rate was varied parametrically from 6%-10%. A sensitivity analysis was conducted to determine if a switch over in the decision would occur. None of the basic conclusions of the report change.

Indexed Calculations
When region, community size, house type, and house age are accounted for, the net cost of residential sprinklers varies tremendously. The 0.05 value for the net cost of installing residential sprinklers varies from a low of $1.4 million per premature death averted (for a new mobile home in a small community in the South) to a high of $35.1 million (for a retrofit of a one and two family dwelling in a medium size community in the west). Some general results and trends are presented below.

For all three home types, new construction was a lower net cost in dollars per premature death averted than retrofit for the same home type. This is due to the higher installation costs for sprinklers in existing homes. In order of net costs, one and two family dwellings were more costly than multi-family dwellings; multi-family homes were, in turn, more costly than mobile homes. These two points are demonstrated by the bar graph in Figure 3 for a small size community (population 5,000 - 10,000) in the South, and in Figure 4 for a larger community (population 50,000 - 100,000) in the West. For both communities the net cost for a new home is always lower than the net cost for an existing home.

A third point is that costs for residential sprinklers in the West are higher than in the other three regions across all community sizes. Costs in the Northeast and North Central follow a trend for all house types (these trends can be seen in Figure 5 for new mobile homes) where costs in the Northeast start off lowest of all regions for the three largest community sizes, population 50,000 and above. After this point, the South drops to the lowest costs and remains there throughout the smallest community size. At community sizes of 25K and smaller, the North Central drops below the Northeast and remains lower than Northeast and higher than South.

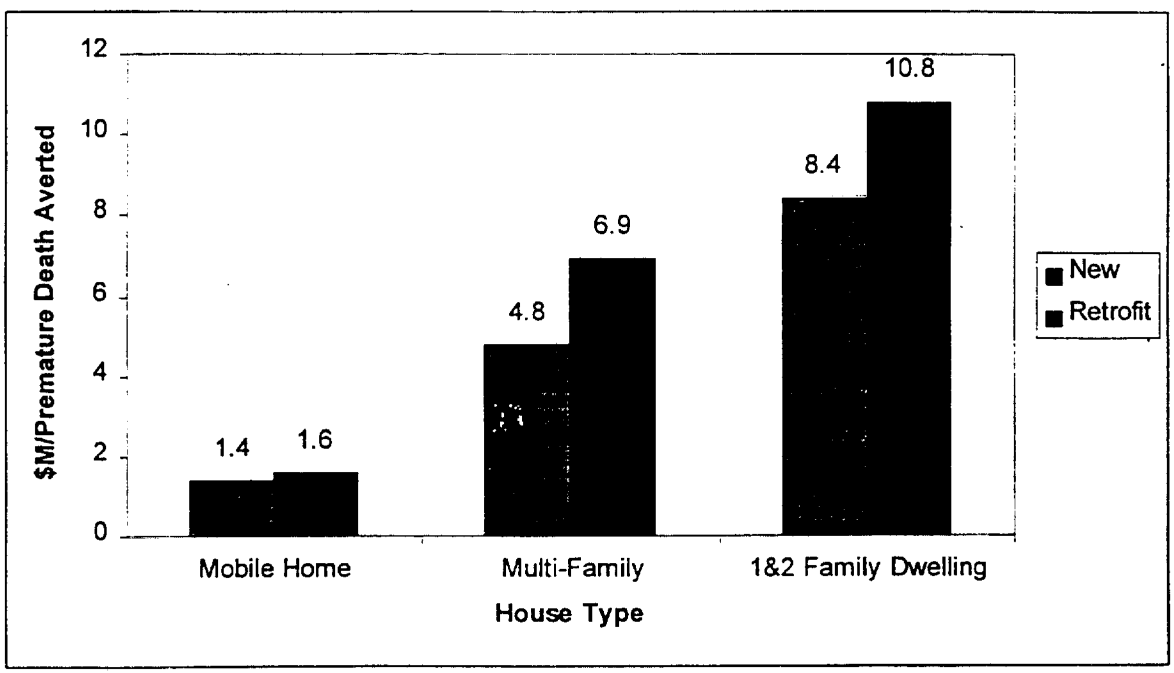

Figure 3. Net Cost of Residential Sprinklers in M$/Premature Death Averted: Comparison of House Type and House Age, Community Size of 5-10K, South Region

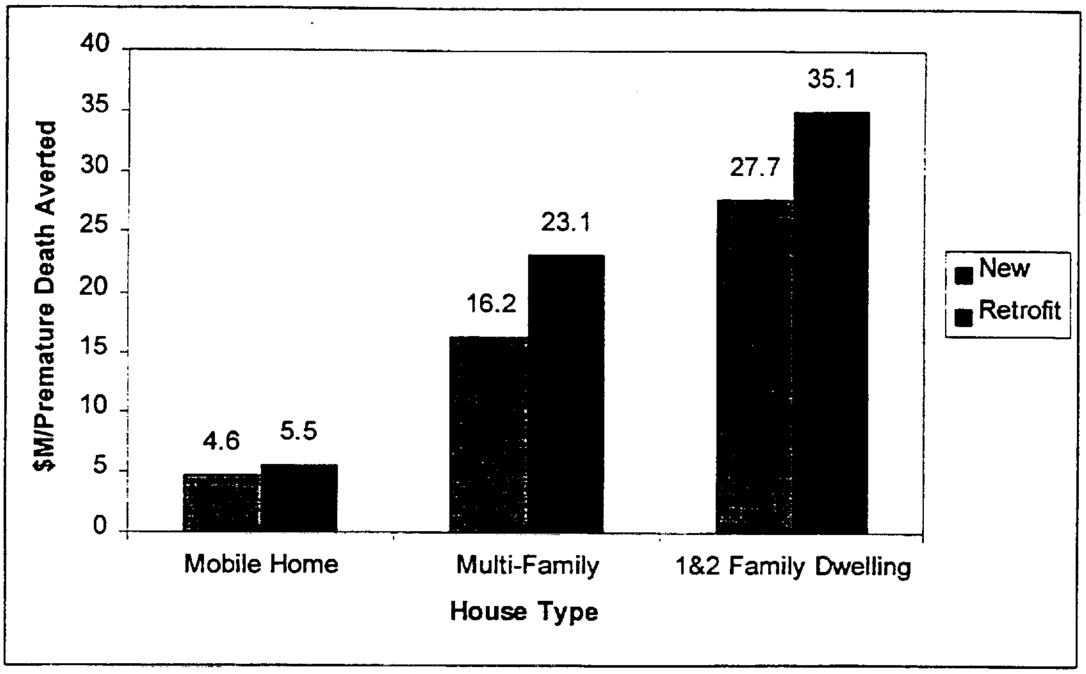

Figure 4. Net Cost of Residential Sprinklers in M$/Premature Death Averted: Comparison of House Type and House Age, Community Size of 50-100K, West Region

Mobile Homes

Since mobile homes are the least costly of the three home types, they are shown in more detail in Figure 5. The net cost of residential fire sprinklers for new mobile homes is presented in Figure 5 in terms of dollars per premature death averted. All regions and community sizes have a cost of three million dollars or less, except for the larger communities in the West. In order to place the cost of installing residential sprinklers in context, in the next section the net cost of installing residential sprinklers is compared to other residential interventions aimed at fatal injury reduction.

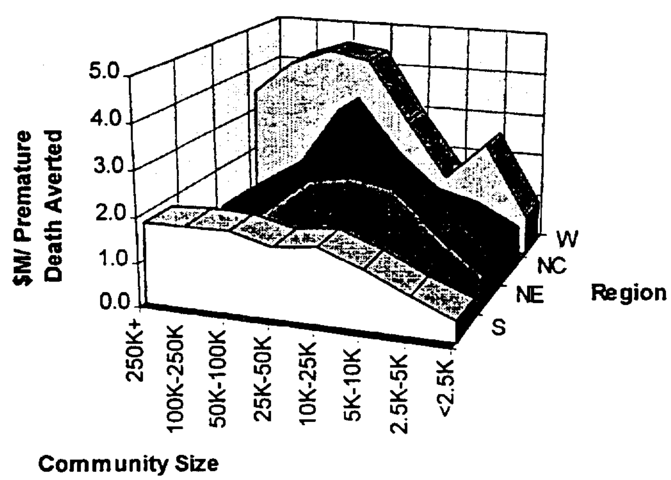

Figure5. Net Cost of Residential Sprinklers in New Mobile Homes: $M/Premature Death Averted

Comparison to other Life-Saving Interventions

An article in Risk Analysis[23] identified over 500 life-saving interventions, reporting their net cost in terms of dollars per life-year saved.[24] The accuracy of the results is limited by the accuracy of the data and assumptions in each original analysis, but the results are believable within an order of magnitude. The interventions reported on range from those saving more resources than they consume, to those costing more than 10 billion dollars per year of life saved.

In this study the cost per life-year saved for residential fire sprinklers was compared to the cost per life-year saved for chlorination of drinking water, banning urea-formaldehyde insulation in homes, installing oxygen depletion sensors for gas space heaters, conducting radon remeditation, mandating child-resistant cigarette lighters, and installing ground fault interrupters. Figure 6 below shows this comparison. The net cost of residential sprinklers shown is an average of the median values of the individual home type calculations. For each home type, thee are 4 regions of the country, 8 community sizes, and 2 house ages. Thus the values shown in Figure 6 are an average of 64 median values. Important findings were that residential fire sprinkler systems are cost-effective for some new mobile homes when compared with other residential fatal injury reduction interventions.

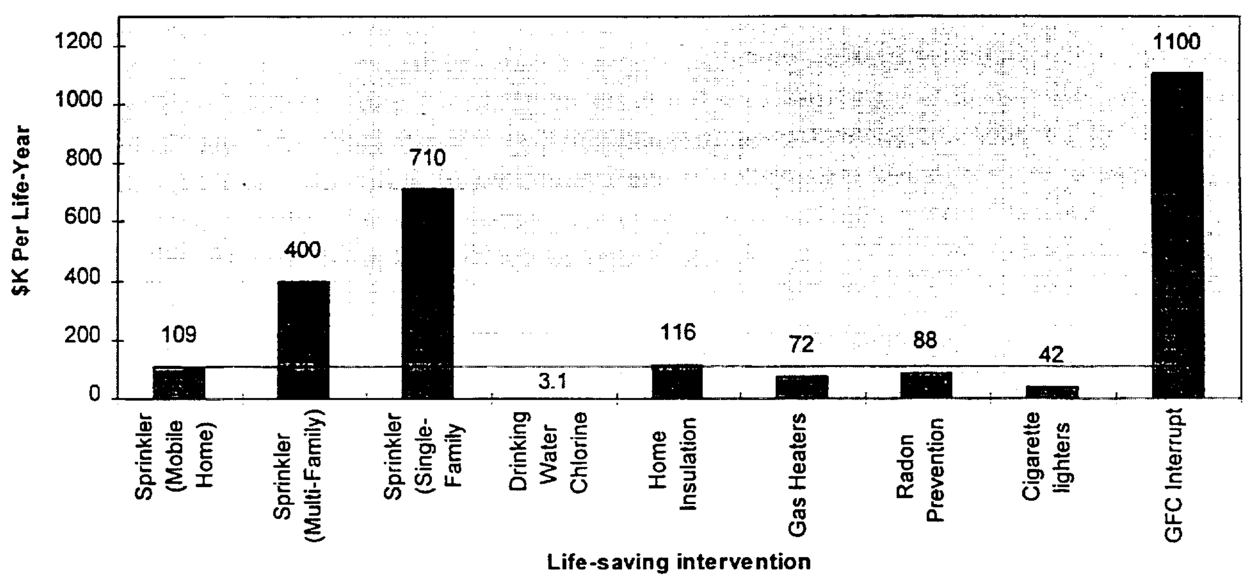

Figure 6. Comparison of Net Cost of Fire Sprinklers in Mobile Homes with Other Residential Life-Savings Interventions

[23] Tengs, Tammy O., et.al., "Five-Hundred Life-Saving Interventions and Their Cost-Effectiveness," Risk Analysis, Vol. 15, No. 3, 1995.

[24] The interventions were classified in four-ways: 1) Intervention Type (Fatal Injury Reduction, Medicine, or Toxin Control); 2) Sector of Society (Environmental, Health Care, Occupational, Residential, or Transportation); 3) Regulatory Agency (CPSC,EPA,FAA, NHTSA,OSHA, or None); and 4) Prevention Stage (Primary, Secondary, or Tertiary).

Another way to gain insight into the benefits and costs of residential fire sprinkler systems is to let total installation cost vary parametrically, to determine at what installation cost switchover in the decision of cost-effectiveness occurs. For example if one chose $3M dollars as an acceptable net cost, it could be determined parametrically what the installation cost needed to meet this is. At an installation cost reduction of 75% of the estimated value, the dollars per premature death averted for all mobile homes is less than $1M per premature death averted, in all regions and across all community sizes. The cost per premature death averted for multi-family occupancies ranges from less than $1M to a high of $3M dollars in the Northeast, South, and North Central regions across all community sizes.

3.5 Iteration: Value of Additional Information

How does uncertainty in the input parameters affect uncertainty in the output parameters? Two important tools for answering these questions are importance analysis and sensitivity analysis.

Importance Analysis

An importance analysis was run to determine the rank order correlation of each input. The rank order correlations for some of the inputs are shown in parentheses below. The importance analysis for the independent variables showed that inputs with rank order correlation on the order of 0.5 and above were the two variables that determined the up front costs of the sprinkler system, installation costs/sq.ft. (0.74), and sq. ft./house type (0.52). Inputs with rank order correlation on the order of 0.2 to 0.4 were: sprinkler reduction factor for death (0.33), annual maintenance costs (0.22), and occupant and fire fighter deaths unsprinklered (0.20). The remainder of the inputs had a rank order correlation of 0.07 or below. The importance analysis was next run at various discount rates to determine if the importance changed as a function of the discount rate. The same top five variables appeared, with the same order of magnitude.

Sensitivity Analysis

An example of one of the sensitivity analysis conducted on this model is that of the discount rate. This study used a baseline discount rate of 8% for evaluation. Varying the discount rate up or down to 6% or 10% did not change any of the conclusions of this report. Median values were used for comparisons.

4.0 CONCLUSIONS

Under a performance-based code system, many decisions have to me made. These decisions are both complicated and subject to uncertainties. The uncertainties encompass more than just measurement uncertainties on empirical variables. Historically, uncertainty has been ignored in this area. Recently, interest in quantification of each type of uncertainty has surfaced. The best approach is to consider all types of uncertainty but only treat uncertainties in the crucial variables, (i.e. uncertainties strong enough to change the final decision). This paper presents a methodology for handling these uncertainties and uses it to make better fire protection decisions. Significant findings presented in this paper include:

1. A performance-based building and fire code regulatory system requires decision making under uncertainty

2. Not all uncertainties in an engineering analysis need to be treated quantitatively
3. A 3-stage approach is presented to determine which variables are crucial to the outcome. Uncertainty is encoded on the crucial variables
4. The appropriate methodology for the treatment of uncertainty depends upon the type of quantity about which the uncertainty exists
5. Effectively treating variability and uncertainty can lead to greater insights
6. Tools such as sensitivity analysis and importance analysis can be used to determine the value of additional information
7. Using comparative analysis and not assigning a "value to life" provides the decision-maker with more information and allows for better decisions.

With the implementation of performance-based codes and standards, interest in the treatment of uncertainty will undoubtedly continue to grow. The building and fire protection communities need to do more work in this vital area.